INDUSTRIALLY FABRICATED BIFACIAL Si SOLAR CELLS WITH n^+-p-p^+ STRUCTURE

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ABSTRACT: Photovoltaic and recombination properties of bifacial solar cells are analyzed. The cells were fabricated in a pilot production line using 6" pseudosquare wafers of 3 to 6 Ω.cm single crystalline Cz Si. Their front efficiency is in the range 18.1 – 18.8 % with back to front short circuit current ratio 74 - 79 %. The design is characterized by high bulk minority carrier lifetime 0.2 – 1 ms, not degraded during the fabrication process, when good starting wafers were used. Effective back surface recombination is in the range 55 - 95 cm/s. Light trapping due to high back internal reflection contributes to current improvement compared to a regular mono facial cell with Al alloyed back. Equivalent efficiency as a quality criteria of a bifacial solar cell is proposed. Routine adjustment of fabrication process promise the increase of average front efficiency above 19 % and equivalent efficiency above 24 %.

Keywords: Silicon Solar Cell, Bifacial, p-type, Boron, High-Efficiency.

1 INTRODUCTION.

High efficiency bifacial solar cells with n^+-p-p^+ (p^+-n-n^+) structure should meet two main requirements. First, low effective back surface recombination, S_{eff}, and a high potential barrier on the back. This can be achieved by a high-low potential barrier formed in the case of p-Si by creation of a boron doped back p^+ layer. The superiority of B as a doping impurity is its high solubility in Si (more than an order of magnitude of the value of Al solubility) [1]. Second, high minority carrier lifetime in the bulk, $\tau_{b.}$ The importance of high lifetime for achieving front and back high efficiencies was shown theoretically [2] and experimentally (for example, [3, 4]). Degradation of τ_b during the cell fabrication process or use of low τ_b starting Si leads to decreased solar cell efficiencies [5]

Indeed, the optical properties of the cell should provide minimal reflectance and effective trapping of photoactive light.

This paper presents an analysis of both optical and electrical parameters of the pilot n^+-p-p^+ bifacial Si cells produced under industrial conditions. Expected effect of routine technological improvements is evaluated.

2 EXPERIMENTAL

2.1 Solar cell structure and fabrication.

The bifacial cells under discussion were fabricated using a gas phase diffusion process for uniform n^+ layer doping by P and diffusion from a surface deposited B source for continuous p^+ back layer formation. The starting material was 6" pseudo square wafers of 3 to 6 Ω.cm single crystalline Cz Si. The front was textured, and the back was treated in different ways – textured or smooth. SiN antireflective coatings were applied to both sides. Contact grids were screen printed on both sides. Measurement results for the bifacial solar cells from a pilot lot of ~10000 samples fabricated under industrial conditions was used as the source of data for analysis.

2.2 Measurements.

I-V curves at one sun illumination (irradiance 1000 W/m^2, light spectrum equivalent to solar one under airmass AM 1.5) and in the dark were measured using h.a.l.m. tracker PV-CTL1 of h.a.l.m. electronics. During the measurements under illumination the receiving of scattered light by opposite cell side was prevented.

The SR300 system of Optosolar was used for front and back spectral response determination. Spectral reflectance and transmission was measured using a Cary 5000, Varian. The self calibration method [6] was used to determine more accurate absolute internal quantum efficiency, IQE, data.

Influence of chuck reflectance on spectral response measurement was evaluated experimentally. Comparative measurements using mirror golden and black chucks demonstrated some decrease in long wavelength spectral response (above ~980 nm) when a black chuck was used instead of a golden one.

Results of IQE calculations based on solar cell transmission and front and back reflectance as well as polished gold reflectance correlate with measurement data. An illustration of chuck effect on cell spectral response (in the form of front IQE) is presented in Fig.1.

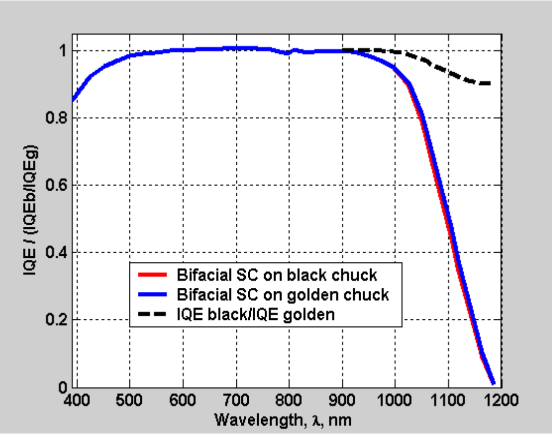

Figure 1: Front internal quantum efficiency of the bifacial cell placed on golden and black chucks. Dashed curve is the correction factor for results determined using gold chuck.

As can be seen, the correction of long wavelength spectral response measured using golden chuck is quite small and does not exceed ~ 10 % at longest photoactive wavelength (see dashed curve). The chuck reflection effect on short circuit current density, J_{sc}, was evaluated by integration over sun spectrum of external quantum efficiency, EQE, measured using golden and black chucks. The evaluation shows that $\Delta J_{sc}/J_{sc}$ is ~ 0.03 %.

The back IQE data were used for the calculation of base recombination parameters: τ_b and S_{eff}.

3 MEASUREMENT RESULTS

3.1 Solar cell internal quantum efficiencies.

Spectral response and IQE data are effective tools for illustration and analysis of the physical properties of solar cells. Fig. 2 represents the front IQE of a bifacial cell as well as of a common mono facial cell with an Al alloyed back. Both cells were produced using the same type of starting Si wafers. Front spectral reflectances of both cells are identical and also shown.

No difference in short wavelength spectral response of the two cells can be seen verifying the same properties of the emitters of both cells.

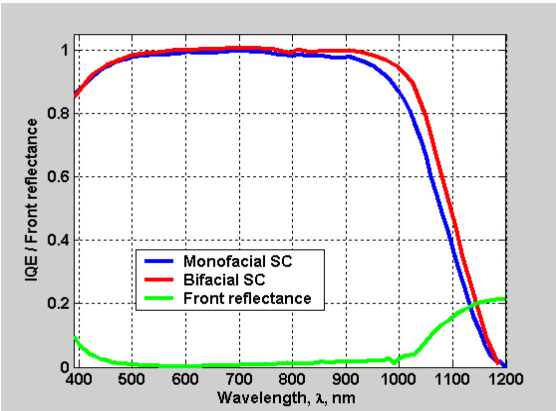

Figure 2: Front internal quantum efficiency of bifacial and mono-facial solar cells fabricated using the same starting Si.

Improvement in long wavelength spectral response in a bifacial cell compared to a mono-facial cell adds ~0.4 mA/cm^2 to photo generated current density under sun illumination. Whereas short wavelength spectral response is determined by emitter properties, the long wavelength spectral response depends on bulk lifetime and back surface recombination velocity as well as on optical properties of the cell structure. Substitution of alloyed Al on back by boron BSF leads to increase of internal cell back reflection $R_{in\ b}$ from ~ 0.6 to 0.76±0.05 and therefore to a better trapping the light**.** Improved light trapping is effective in combination with low recombination losses in the base region.

For more detailed characterization of recombination parameters of the bifacial cell the front IQE should be analyzed in combination with the back IQE. Fig. 3 demonstrates the back IQE of two bifacial samples: one with a smoothly etched back and one with a slightly textured back. The back SR of the two cells is different due to variations of the fabrication process, but back IQE of all the fabricated cells in a given lot are between these two. The back IQE data shown in Fig. 3 were used for evaluation of S_{eff} at the inner border of the p$^+$- layer. This was done in a model of a cell with zero thickness of a p$^+$-layer by comparison of experimental IQE data with the calculated curve. For such a comparison the experimentally determined back IQE data were corrected for recombination losses in the p$^+$- layer. The correction was made assuming that recombination losses of carriers generated inside p$^+$-layer for each wavelength are equal to recombination losses at wavelength 400 nm. The corrected IQE points for two cells are shown in Fig. 3. The data points for these two cells ~coincide if thickness of the high recombinative part of p$^+$- layer is assumed ~ 0.57 µm. The experimental points fit very well to the simulated curve, which was generated by the PC 1D program in assumption of zero thickness of the p$^+$- layer.

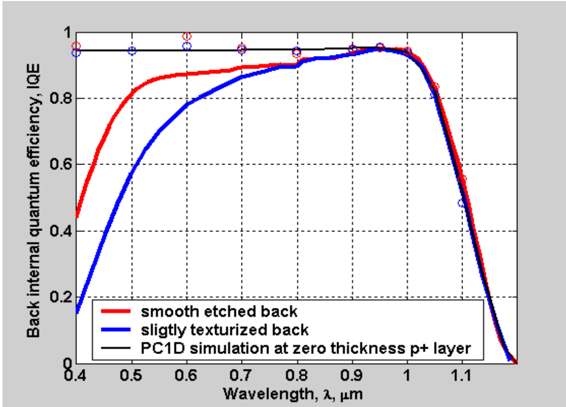

Figure 3: Range of spectral dependences of back internal quantum efficiency of bifacial solar cells of an industrially fabricated lot.

PC 1D simulated curve fitted to the corrected IQE data is used for S_{eff} and τ_b determination. The high base recombination parameters are needed for good agreement of calculated curve and experimental data: S_{eff} is in the range of 55 - 95 cm/s and the respective bulk minority carrier lifetime τ_b values are 0.2 to 1 ms. The low S_{eff} in an bifacial cell is the important factor determining higher front long wavelength response of bifacial cells compared to regular mono facial cells with Al alloyed backs. The lower back S_{eff} in bifacial cells with B doped p$^+$ layer compared to Al alloyed cells is due to superior B solubility in Si and therefore a higher p-p$^+$ barrier. The above mentioned S_{eff} in bifacial cells should be compared with 400 cm/s or more for cells with Al alloyed backs [7]. Obviously low S_{eff} is very useful for high back response. Back IQE demonstrates with more confidence than front IQE, retention (or improvement) of bulk recombination rate during fabrication processing: $\tau_b \geq 0.2$ ms in the cells of Fig. 3.

3.2 The I-V curves.

The front and back I-V curves of a bifacial cell of ~18.6 % front efficiency at simulated 1 sun illumination are shown in Fig 4. Compared to regular mono facial cells with the same front design and fabricated on the same production line, the bifacial cell is distinguished by improved front I_{sc} (by ≥ 1 %) and V_{oc} (by ≥ 10 mV).

A more comprehensive analysis of fabricated bifacial cells can be done based on Table 1. This Table contains the approximate statistical data for the batch (excluding breakage and samples made using mistake operations). Despite a relatively wide range of cell parameters, due to some technological variations in the fabrication process, efficiencies of the cells are quite high and bifacial symmetry exceeding 74 % is good. It should be taken into consideration that the cells were fabricated using an "old fashioned" printed contact system with relatively high area coverage (≥7.2 %). The data demonstrate an intrinsic superiority of the bifacial n^+-p-p^+ design and fabrication technology used. The main imperfection of the cells is their relatively low V_{oc}. The above mentioned S_{eff} values (95 cm/s or less) in combination with τ_b ≥ 0.2 ms do not limit V_{oc} at levels lower than ~660 mV. The shown in Table 1 expected parameters of bifacial solar cells are evaluated using the best achieved values, excluding V_{oc} which can be improved without any significant change in fabrication processing.

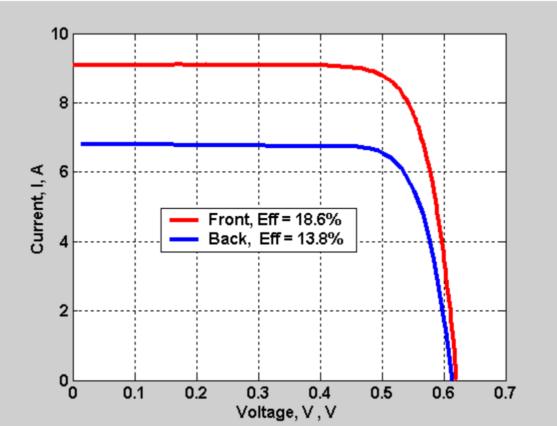

Figure 4: Front and back I-V characteristics of a typical bifacial cell at one sun illumination.

Table 1: Approximate statistical data for an industrially produced ~ 10000 bifacial cell lot

Parameter	Range	Average	Expected
I_{sc}, mA/cm^2	37.5-38.1	37.7	38.1
V_{oc}, V	616 - 629	622	639
FF, %	78 -79	78.5	79
Eff. (front), %	18.1-18.8	18.45	19.2
(I_{scb}/I_{scf})x100, %	74-79	75	79

4 DISCUSSION

The industrial pilot production demonstrates that the design and fabrication technology of bifacial n^+-p-p^+ Si solar cells provides the achievement of the main requirements for high efficiency cells.

A very effective high-low back barrier is formed by B doping of the p^+ layer resulting in low S_{eff}. Despite all the scattering of measured back IQE due to variations in fabrication process the S_{eff} values of cells are low and in the range 55 – 95 cm/s. The range is determined by the limited accuracy of the agreement between calculations and experimental data. However, even the highest values limit the voltage at the 660 mV level.

Retaining very high τ_b is possible even in the Cz wafers with very high starting τ. The measured τ_b are in the range 0.2 – 1 ms (again determined by limited accuracy of simulation and experiment agreement). High τ_b is an important factor for achieving the highest cell efficiency.

Effective light trapping due to high back internal reflectance ($R_{in\ b}$ ≈ 0.76) leads to a significant contribution in I_{sc} improvement compared to a regular mono facial cell. Measured recombination and optical parameters of fabricated bifacial cells promise a further increase of cell parameters. Front efficiency above 19.5 % should be achieved due to a decrease of contact coverage to the level already realized in the PV industry.

Low S_{eff} in combination with large τ_b provides a high symmetry factor. The best back IQE shown in Fig. 3 in combination with optimal SiN antireflective layer should result in $I_{sc\ b}/I_{sc\ f}$ exceeding 83 %.

The above data of high cell efficiency and no degradation of high starting lifetime during the fabrication procedure leads to conclude that Cz p-Si used for fabrication of n^+-p-p^+ bifacial cells can be competitive with n-Si as a material for high efficiency cell production.

The quality of bifacial cells cannot be evaluated only by front efficiency as far a regular mono facial cell. The adequate quality criteria may be given by evaluation of energy generated by a solar cell. This can be described by "equivalent efficiency". (See Table 2.) Equivalent efficiency is determined as efficiency of a mono facial cell needed for generating the same energy as a bifacial cell under the given conditions.

Table 2: Equivalent efficiency as quality criteria of bifacial cell.

Front efficiency, %	Back contribution (energy gain), %	Equivalent efficiency, %
18.5	10 (field installation with low albedo)	20.35
18.5	20 (roof installation with intermediate albedo)	22.2
18.5	25 (roof installation with high albedo)	23.1

The data in the Table are based on the outdoor monitoring of bifacial modules under different working conditions [8, 9]. The table demonstrates what the values of equivalent efficiency are for a bifacial cell described here with front efficiency of 18.5 %. It can be seen that the equivalent efficiency of these bifacial cells is always higher than 20 % and for most typical applications exceeds 22 – 23 %.

It is obvious that equivalent efficiencies above 24 % will be achieved when cell parameters improvement presented in the Table 1 will be realized.

5 CONCLUSIONS

1. n^+-p-p^+ with uniformly B doped p^+-layer is a promising structure for industrially produced terrestrial bifacial cells.
2. Pilot batches demonstrate retained high bulk lifetime τ_b and provide S_{eff} in the range 55 – 95 cm/s.
3. Low S_{eff} in combination with effective light trapping contribute to increased long wavelength response, photo generated current (by ~ 0.4 mA/cm^2) and efficiency (by ~0.5 % abs).
4. Back to front short circuit current ratio is in the range 74 – 79 %.

5. Equivalent efficiency as quality criteria of the bifacial cell achieved 22 - 23 % in the typical applications.
6. Improvement cell efficiency above ~19 % is expected after tuning existing fabrication processes. This will result in >24 % equivalent efficiency.
7. High quality starting Cz p-Si can compete in the near future with n-Si as a material for high efficiency bifacial cell production.

Acknowledgments

We are grateful to our colleagues S. Hasenauer, D. Obhof, G. Wein and D. Zimmerling for their decisive contribution in the experiments.

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